

## SPACE STATION SOLAR ARRAY JOINT REPAIR

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**ABSTRACT:** In Oct 2007 the International Space Station (ISS) crew noticed a vibrating camera in the vicinity of Starboard Solar Alpha Rotary Joint (SARJ). It had less than 5 months of run time when the anomaly was observed. This ~3.2 meter diameter bearing joint supports solar arrays that power the station critical to its operation. The crew performed an EVA to identify what was causing the vibration. It was discovered that one of the 3 bearing tracks of this unconventional bearing had significant spalling damage. This paper discusses the SARJ's unique bearing design and the vulnerability in its design leading to the observed anomaly. The design of a SARJ vacuum test rig is also described along with the results of a life test that validated the proposed repair should extend the life of the SARJ a minimum of 18 years on-orbit.

### INTRODUCTION

**SARJ Description:** The Solar Alpha Rotary Joint (SARJ) points four large (35 meter long by 12 meter wide) solar array panels toward the sun during each 90 minute orbit around the earth (Figure 1). There two SARJs (Port and Starboard) aboard the ISS.

Each SARJ consist of ~ 3.2 m diameter race rings (primary and redundant) that are supported by a single set of 12 trundle bearing assemblies (Figures 2 and 3). The fundamental concept of a trundle-based bearing configuration for the SARJ is described in [1]. Primary and redundant drive motors engage a large ring gear that is machined into the race (not shown). The trundles can be flipped from primary to redundant race ring in the event of a SARJ failure.

The trundle bearing assembly consists of three 440C roller assemblies which support a triangularly-shaped race ring (Figure 3). This ring is made from AISI 15-5PH stainless steel with a nominal 175 micron thick nitrided case which serves as a hardened wear resistant surface. The original design assumed nearly pure rolling with rollers having a thin ion-plated gold coating and therefore did not rely on liquid lubrication which could degrade with time. The rollers are supported on tapered roller bearings with a redundant inner sleeve bearing that would automatically rotate in the event of a tapered bearing failure. Each trundle bearing roller assembly is mounted to the stationary housing through a camber pivot (see Figure 3). This was intended to allow the rollers to lay flat against the race surface if there was some disortion. An adjustable, spring preload arm applies ~ 3900 N of preload to each roller contact.

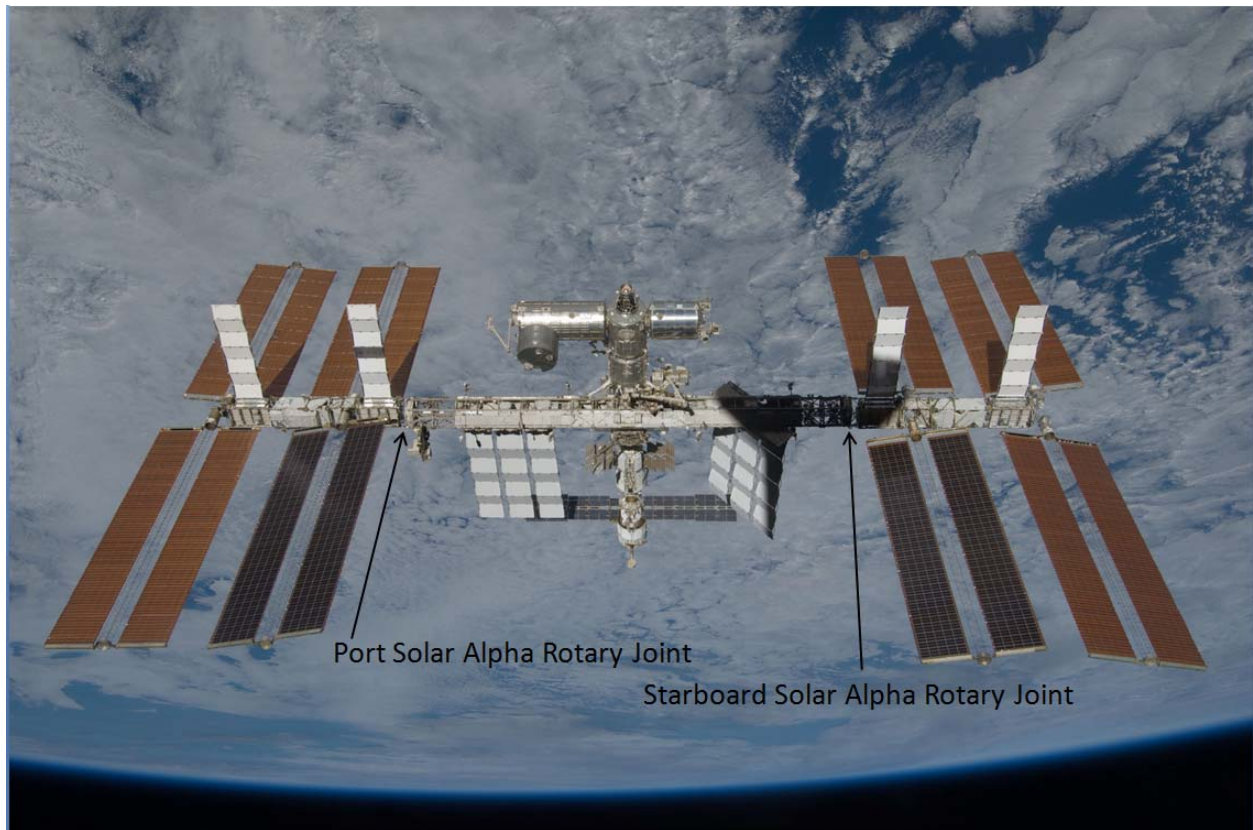
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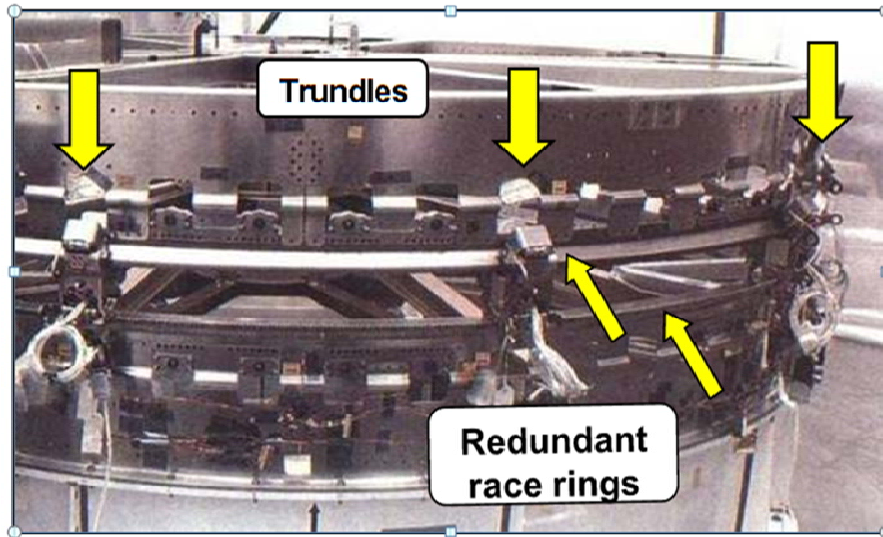
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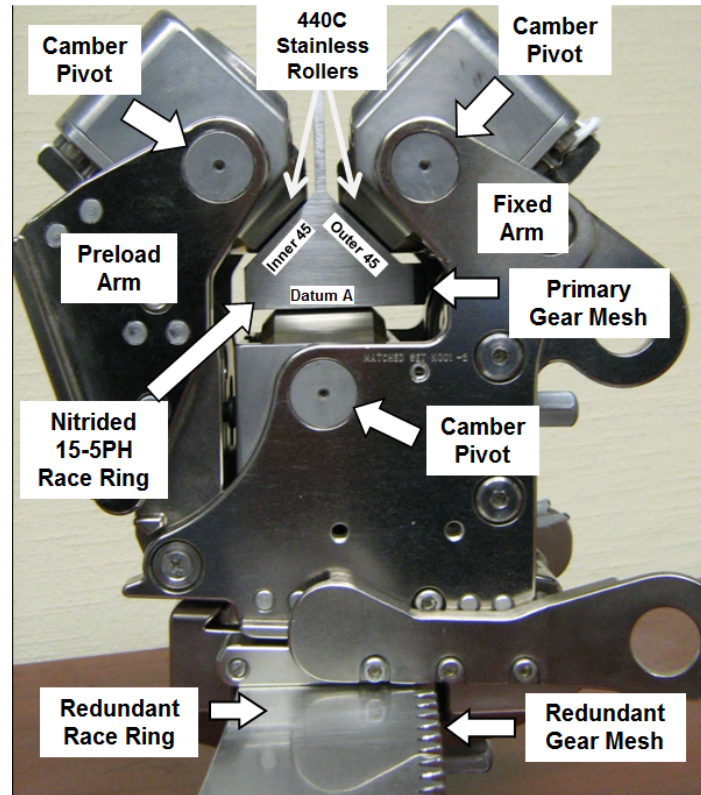
A gear mesh to drive the SARJ was cut into the race ring at its outside diameter as shown in Figure 3 (note that the centerline of the assembly is to the left of this figure).



**Figure 1: SARJ orients port & starboard solar array wings to sun**



**Figure 2: Trundle Bearing Assemblies (12) support a 3.2m-diameter race rings (redundant)**



**Figure 3: Trundle Bearing Assembly showing rollers trapping triangular shaped race ring. Note that camber pivots allow roller assembly to align flat against race ring surface**

**SARJ Starboard Vibration Anomaly:** The ISS crew noticed vibration on one of the monitoring cameras in the vicinity of Starboard SARJ on 22 Oct 2007. The starboard SARJ had been operating less than 5 months when this anomaly was observed. Velocity traces from the controller showed a significant increase in servo errors after 5 days of monitoring (Figure 4).

The crew was sent out to investigate the SARJ. They found significant race damage on outer 45 deg track (Figures 5). The nitrided case had spalled creating many nitrided case fragments (Figure 6). The increased torque and vibration resulted from the preloaded rollers rolling over the damaged track surface covered with these residual case fragments. However the inner 45 deg and datum A races remained undamaged (Figure 3). Also the Port SARJ races were still in good condition after 14 months of operation at the time of the inspection [1].



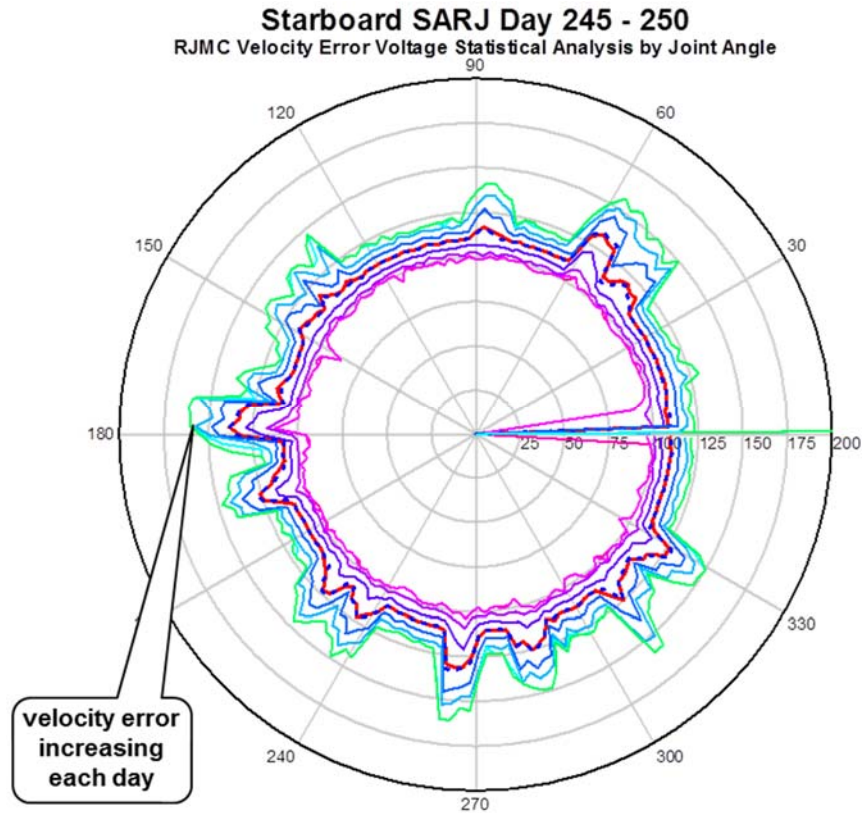


Figure 4: Velocity error trace showed increasing servo errors at several clock positions

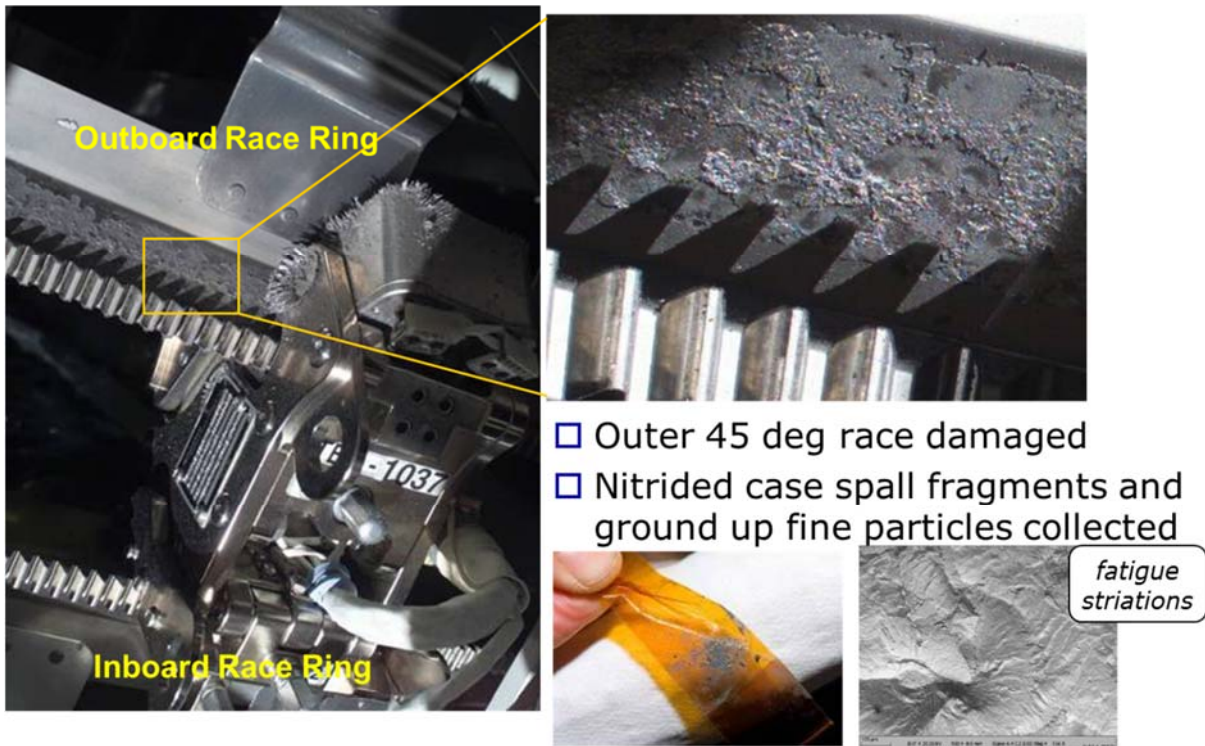
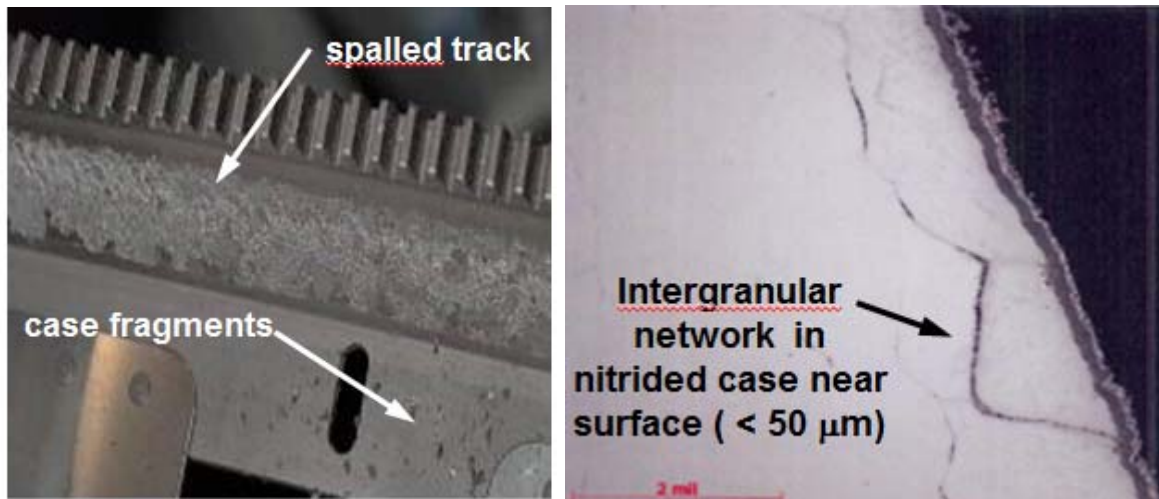


Figure 5: Damaged On-orbit Starboard SARJ 45 deg race ring track



**Figure 6: Close up of spalled track and cross-section through case showing intergranular separations (voids)**

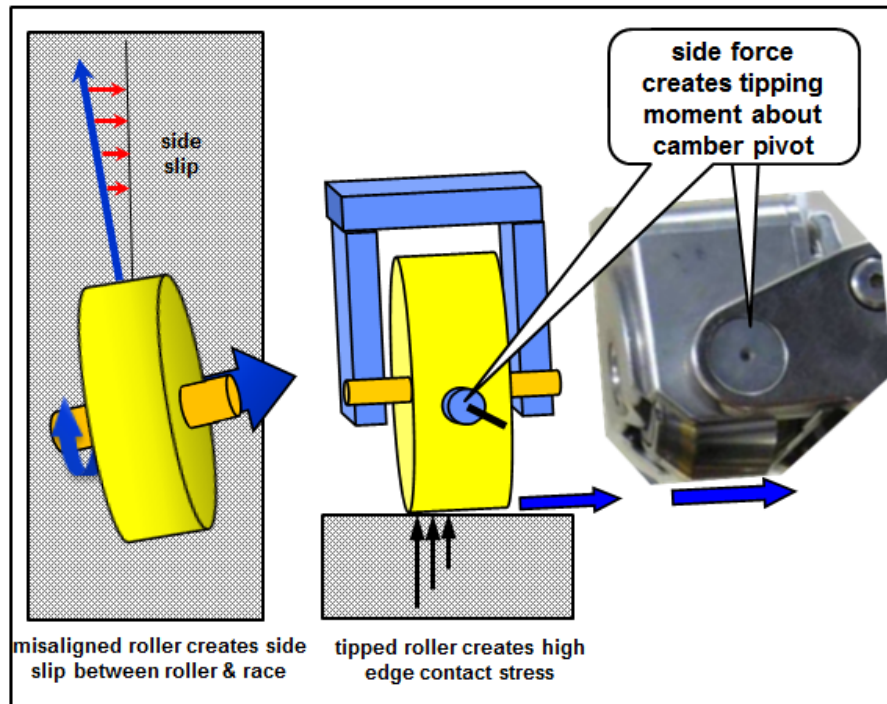
**Root Cause:** A Government –Industry team was formed to determine root cause. It was determined that the damage to the race was caused by an unexpected sequence of events. Although the rollers were aligned with the race track with in a small degree of error (within  $\pm 1$  degree) it was discovered that even a slight misalignment ( $< 0.5$  deg) could cause the roller to pivot about the camber pivot axis. This would cause high roller edge loading because of the high surface friction forces from inadequate lubrication .

As shown in Figure 7 the small misalignment (a.k.a. mistracking) caused a side slip velocity to be generated relative to the race rotation velocity vector. This side slip velocity in turn generated an axial contact force that caused the roller to tip about the camber pivot axis. To react this moment load, the load distribution across the roller width shifted to the outboard edge generating high roller edge contact stresses ( $> 5$  GPa maximum Hertz stress). The high contact edge stress coupled with intergranular networking (crack-like separations) just below the race surface ( $< 50$  microns) initiated the spalling observed on the damaged race. (Figure 6). [2-5].

**Repair:** Although the SARJ was designed with a redundant races and drive motor that allowed switching between the primary and redundant races, this would be a major undertaking to implement. Not only would it require considerable astronaut EVA time plus planning but a temporary Solar Array wing holding structure would need to be built at considerable cost.

Fortunately analysis indicated that lubricating the damaged and undamaged tracks with grease would likely lower the equivalent friction coefficient below the roller tipping threshold of less than  $\sim 0.4$  [2]. Clearly this would be far easier and less risky repair to implement if it could be demonstrated that greasing the races would be effective in extending SARJ track life. So planning was begun on a high fidelity test rig with the goal of demonstrating that grease lubrication would prevent additional damage to the Starboard SARJ. The goal was to prove that the SARJ could safely run another 18

years on orbit with a single application of grease which meant that the life test would have to achieve an equivalent 36 years of on-orbit operation considering the required 2X life test margin of safety.



**Figure 7: Tipping mechanism created by slight misalignment coupled with high contact friction which causes the roller to tip about pivot axis**

## SARJ LITE TEST

The SARJ LITE (Lubrication Interval Test) test rig was built to evaluate the expected life of the proposed grease repairs to both Starboard SARJ and Port SARJ. Of specific interest was to determine the relubrication time intervals needed to maintain acceptable SARJ performance beyond 2028 the NASA hardware certification goal.

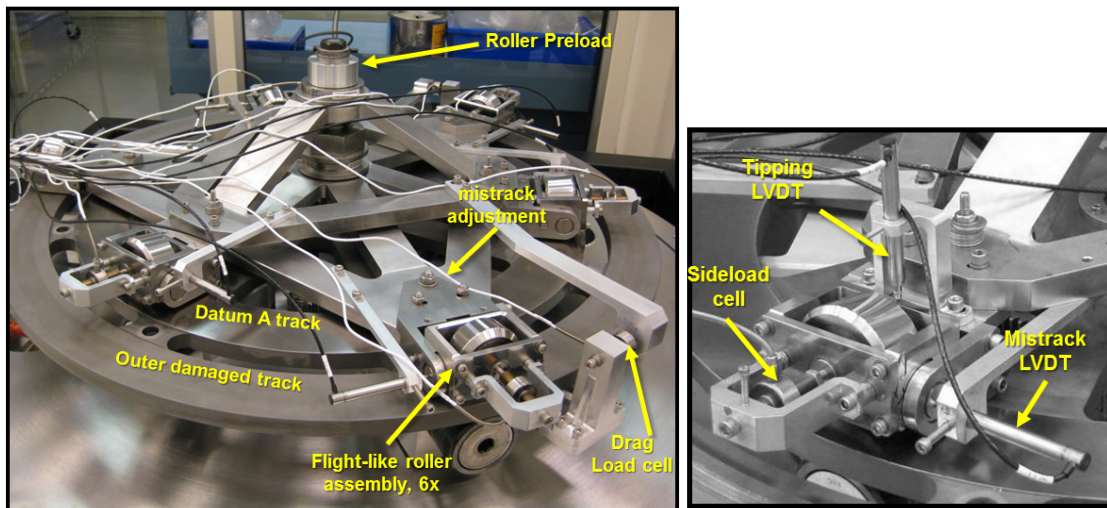
**Test Rig Description:** The SARJ LITE tester uses a flight-like, nitrided race plate with dual track surfaces to simulate the damaged (outer 45°) and undamaged flight races (Figure 8). The outer track was artificially damaged using a friction-stir welding machine and it and the inner track were lubricated with Braycote 602 flight grease using the proposed flight lubrication process (see Figure 9). Note that the intergranular network within the nitrided case of the SARJ test plate, believed similar to the Port SARJ, was less extensive (~ 80% less area) than the Starboard [4]. However the pre-test damage



inflicted into the outer 45° test track was intentionally more severe than observed on-orbit to help compensate for this.

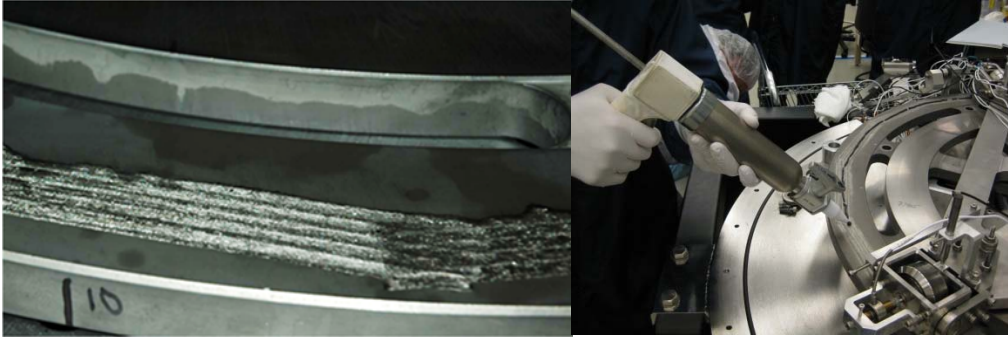
The test rig track diameter was scaled down in size by a factor of 3 to comfortably fit inside a custom vacuum chamber. Three, well instrumented, full size trundle roller assemblies contacted each test track. They were supported by an inner and outer spider which provided flight preload and flight-like roller spacing. Rollers have flight diameters, materials, hardness, surface finish and profiles plus they were preloaded at flight preload levels. The race plate was supported by a set of 3 cam follower rollers for each track. The support rollers were mounted directly underneath the plate in line with the trundle roller to react the contact load with minimal deflection. The rotating drag torque of each of the roller sets (45° outer and Datum A) was measured independently by a load cell-instrumented torque arm (Figure 8).

Figure 8 also shows a close up view of the trundle roller assembly instrumentation. Each roller is equipped with a thrust load cell to monitor side traction loads, a measure of the quality of the lubrication between the roller and the race. Increases in side load is a direct measure of an increase in the contact friction coefficient. The rollers were intentionally misaligned at angles that were slightly larger than flight using the “mistrack” LVDT. The roller cradle had a camber pivot which allowed the roller to tip as measured by a “tipping” LVDT. Rollers were preloaded against the race at flight levels. These parameters were recorded and trended through the test as an indicator of lubrication health.



**Figure 8 SARJ LITE test rig showing Outer 45 damaged track and undamaged datum A track each contacted by three well-instrumented flight-like roller assemblies .**





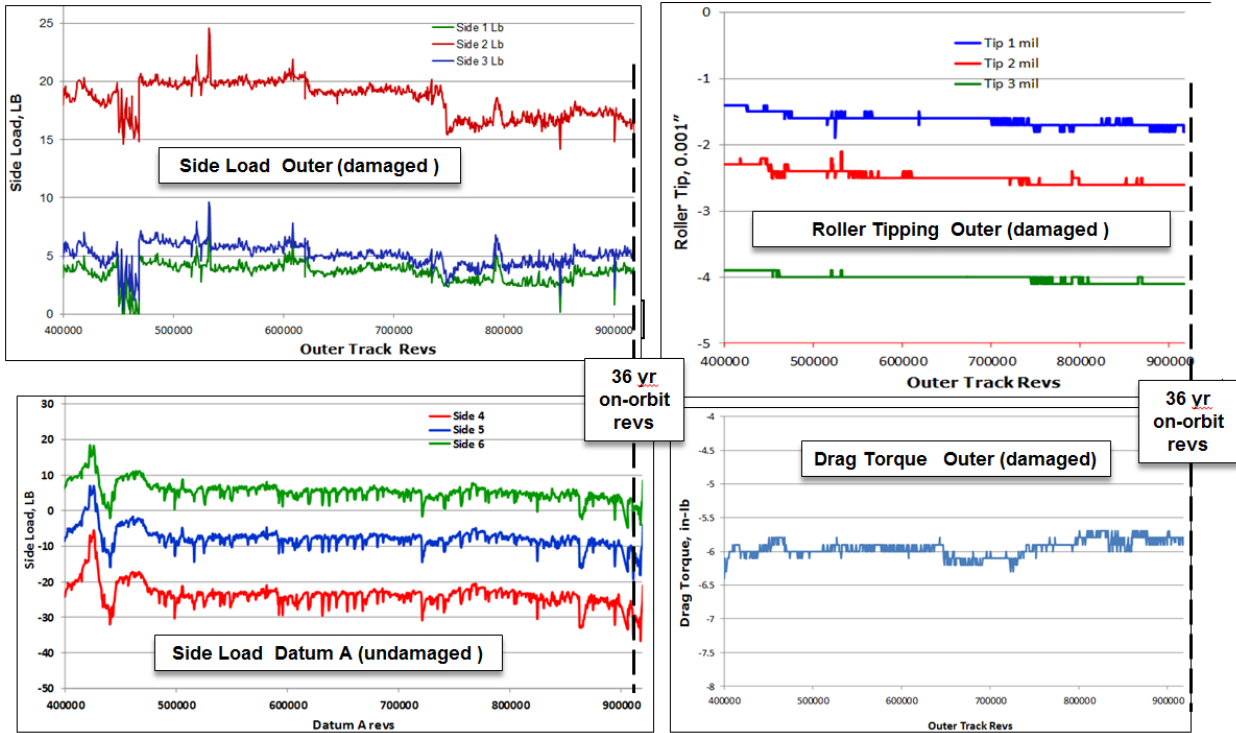
**Figure 9: Predamaged Outer 45°Race which was lubricated using the flight process**

## TEST RESULTS

The SARJ LITE rig test rig ran nearly continuously for about 5 years accumulating ~ 12.6 million revolutions. This is equivalent of 36 flight years of operation (2X the 18 years extension goal) before the test was halted unfailed.

As shown in Figure 10, the individual roller side loads of both damaged and undamaged tracks remained relatively constant throughout the test. The drag torque on the outer track also remained relatively constant. The relatively stable behavior of these health indicators confirms that grease degradation was relative minor over the life test. The only exception was when the rig was temporally stopped because of a test rig problem. These interruptions caused the baseline to shift slightly due to zero shifts in the load cell that were related to changes in ambient temperature changes. Algorithms were developed to help calibrate out these temperature variations. However the discontinuities still were present but did not influence the health trending taken between these events.

Another important parameter that was important to trend was roller tipping. As mentioned previously it was determined that roller mistracking coupled with high surface friction from dry roller contact was the root cause of the SARJ failure. The high contact stress due to roller edge loading as a result of mistracking caused the roller to spall the nitride case. During the test a LVDT was mounted to the spider to measure the degree of tilting of the trundle roller cradle assembly. The tilting angle will increase if side load traction were to increase. The tilting angle also remained relatively constant throughout the test. This is essentially an independent confirmation that the roller contact friction levels also remained stable during the test (Figure 10).



**Figure 10 Test results showed relatively steady contact friction levels, roller tipping and drag torque throughout life test**

At the end of the test the two test tracks were examined for damage and lubrication degradation (see Figure 11). The initially undamaged inner track showed minor pitting (spalling) of surface. The track was still in good condition. The outer berm was still in place and was evidently re-supplying the rolling track with a slight oil film at the conclusion of the test.

The outer track show a modest degree of additional wear on the raised surfaces relative to the intentional pre-test damage created to represent starboard SARJ. Degraded grease was retained in the man-made furrows in the track. Also berms were healthy on both sides.

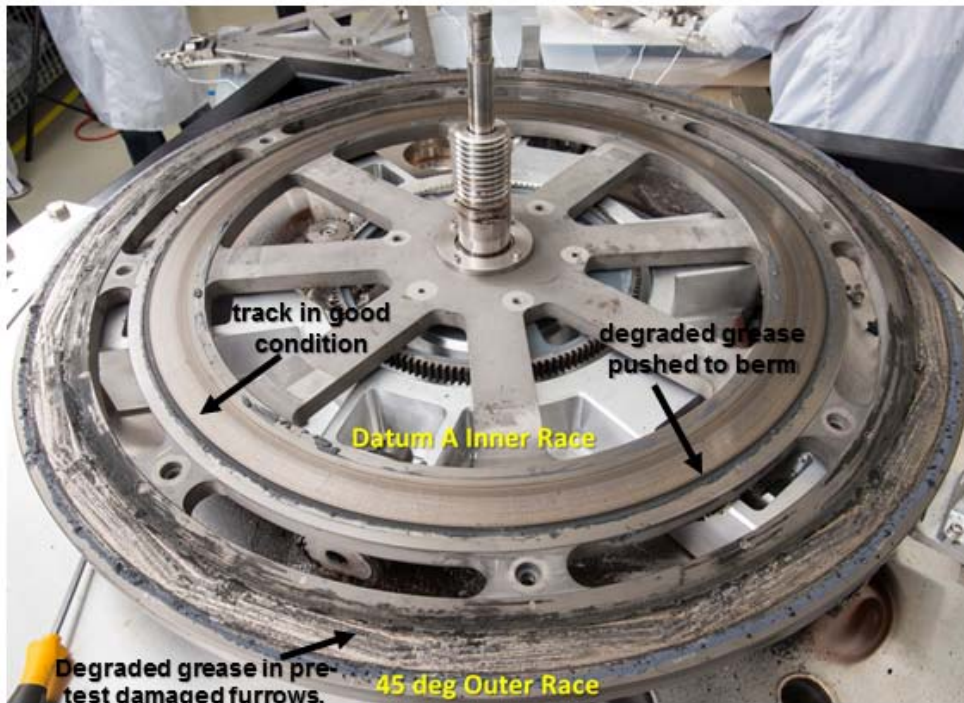


Figure 11 Track appearance at end of test

## CONCLUSION

The SARJ LITE test achieved the planned 36 equivalent on-orbit year milestone (2X the mission extension life of 18 years). The vital health indicators for the simulated damages starboard 45 deg race, the undamaged Datum A race and the rollers remained stable throughout the test. This indicates that a single application of grease lubrication to the flight starboard and port SARJ tracks will be effective for many years to come.

## REFERENCES:

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- [4] Dasgupta, R., Figert, J., and Martinez, J., "NASA Internal Briefing: SARJ Lite Samples Metallurgical Analysis", SARJ Materials & Processes Team, 19 August 2008-unpublished

**Key Words:** Solar Alpha Rotary Joint, International Space Station, Lubrication,